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The DRS Interferometric Displacement Sensor

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Disturbance Reduction System

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- Technology validation of sensor and thrust-producing technologies to control a space vehicles flight path so the payload responds only to gravitational forces.

Sensor: Stanford University, Stanford, CA

Thruster: Busek Company Inc. Natick, Mass.

- Launch 2006 as NASA's Space Technology 7 project (ST7)
  - Piggy-backing on ESA's SMART-2 Mission

DRS Technology Objectives

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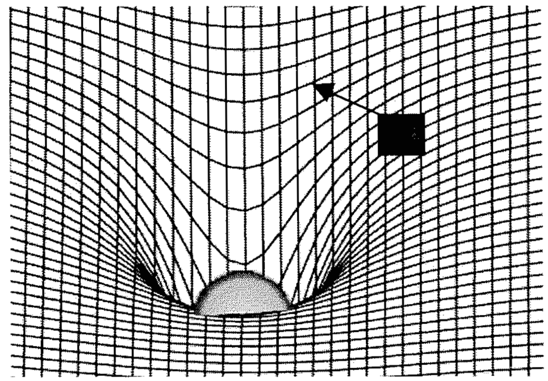
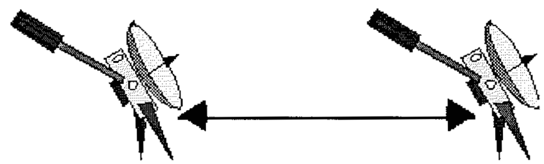
- Validate that a test mass follows a trajectory determined by gravitational forces only within 3×10^{-14} $m/s^2/\sqrt{Hz}$
  - Low acceleration noise is needed for study of general relativity, planetary gravity, gravitational waves



- Validate spacecraft position control to an accuracy of <10 $nm/\sqrt{Hz}$
  - Spacecraft position control is required for separated-spacecraft interferometers which do not use internal delay lines



DRS Concept

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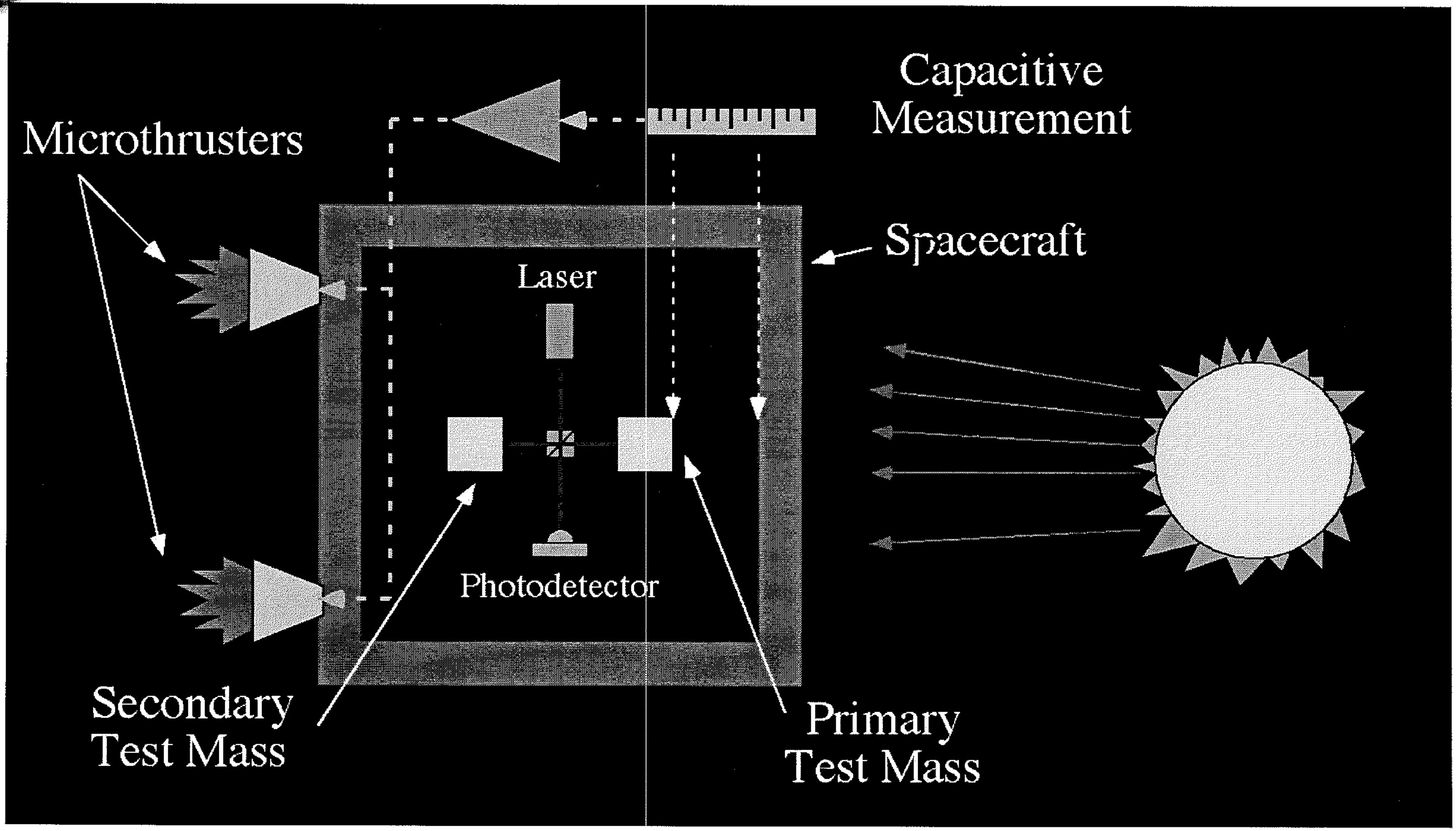

- The DRS instrument package consists of
  - Two gravitational reference sensors
  - Microthrusters for spacecraft position control
  - Interferometer to measure the distance between the two test masses.

DRS Technologies

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- Gravitational Reference Sensors
  - Test mass noise < 3×10^{-14} m/s^2/√Hz, 1 mHz to 10 mHz
  - Measurement of position to < 3 nm/√Hz, 1 mHz to 10 mHz
  - Accelerometer mode
    - Validation of thrusters
  - Force noise diagnostics
    - Validate noise models
- Micro-Newton Thrusters
  - 1-20 μN range
  - Control precision adjustment < 0.1 μN
  - Noise < 0.1 μN/√Hz, 1 mHz to 10 mHz
- *Interferometer is not a new technology*
  - Can be completely tested on ground
  - Is used in DRS for validation only - I.e. independent (out-of-loop) detector

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Flight Validation Rationale

- Must be validated in space
  - 1 g environment on Earth makes ground testing impossible
- Must be in orbit far from Earth
  - Difference in gravitational force on two test masses must be small to validate instrument performance
    - Requires orbit at GEO altitude or higher
- Must have mechanically, thermally stable environment
  - Spacecraft must be in constant orientation during DRS tests
  - Thermal isolation system needed for DRS
    - Spacecraft eclipses need to be avoided
- ESA SMART-2 spacecraft suitable host
  - Will operate ~ 0.1 AU from Earth

Flight Activities

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- DRS operations will take 90 days
  - DRS operates only at specific times
  - Spacecraft needs to be in quiet state
    - No maneuvers
    - No moving parts
    - No changes in power dissipation
  - Spacecraft will establish a nominal orientation and dead band
    - DRS should maintain orientation
    - If orientation dead band exceeded, DRS will be shut off
  - DRS tests will consist of a series of experiments of 1-3 days each
    - Experiments can be scheduled non-consecutively
    - Experiments can be repeated if necessary

Flight Validation Measurements

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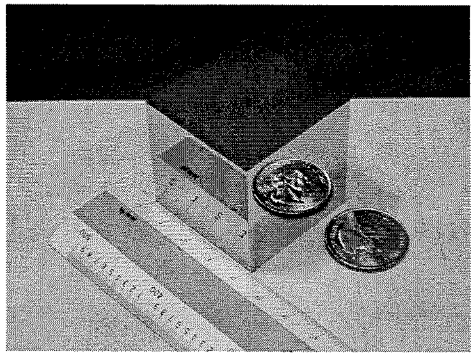
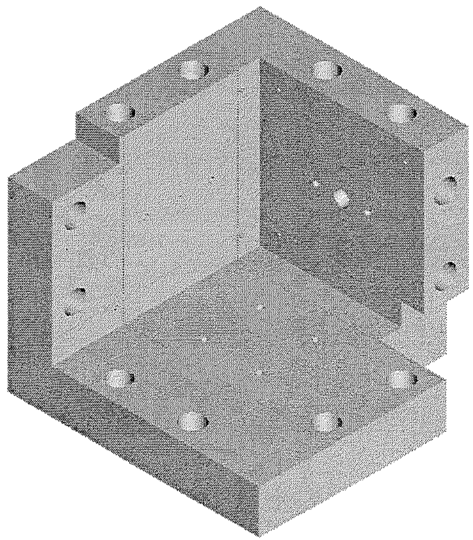
- GRS in accelerometer mode validate thruster performance
  - Can use two GRS to compare calibrations
  - Initial thruster calibration to be used for setting spacecraft control parameters
  - Calibration will be repeated several times over 6 months to check stability
- Fire thrusters to center spacecraft on one GRS test mass
  - GRS position measurements used for control and validation
  - Interferometer readout cross-checks GRS in one direction
- Fire thrusters to orient spacecraft around two test masses
  - GRS position measurements used for control and validation
- Verify acceleration noise on test masses
  - Laser interferometer compares acceleration of two test masses
- Verify force noise model verification
  - Apply known perturbations to see that response is as predicted

GRS Description

- GRS consists of;
  - A freely-floating test mass within a housing,
  - Position measurement of the test mass w.r.t. housing
  - Control of test mass orientation
  - Charge control subsystem
- The proof mass must be isolated from;
  - Solar magnetic field
  - Solar radiation pressure
  - Residual gas pressure
  - Thermal radiation pressure
  - Charging by cosmic rays
  - Spacecraft self-gravity
  - Spacecraft magnetic fields
  - Spacecraft electric fields



GRS Test Mass



GRS Housing Assembly

GRS Requirements

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ITEM	REQUIREMENT
Sensitive Axis Acceleration Noise	**3×10^{-14} m/s^2/$\sqrt{\text{Hz}}$**
Trans. Axis Acceleration Noise	**None**
Sensitive Axis Position Sensitivity	**10×10^{-9} m/$\sqrt{\text{Hz}}$**
Trans. Axis Position Sensitivity	**2.5×10^{-6} m/$\sqrt{\text{Hz}}$**
Orientation Control Noise	**1×10^{-6} rad/$\sqrt{\text{Hz}}$**

DRS Performance Limits

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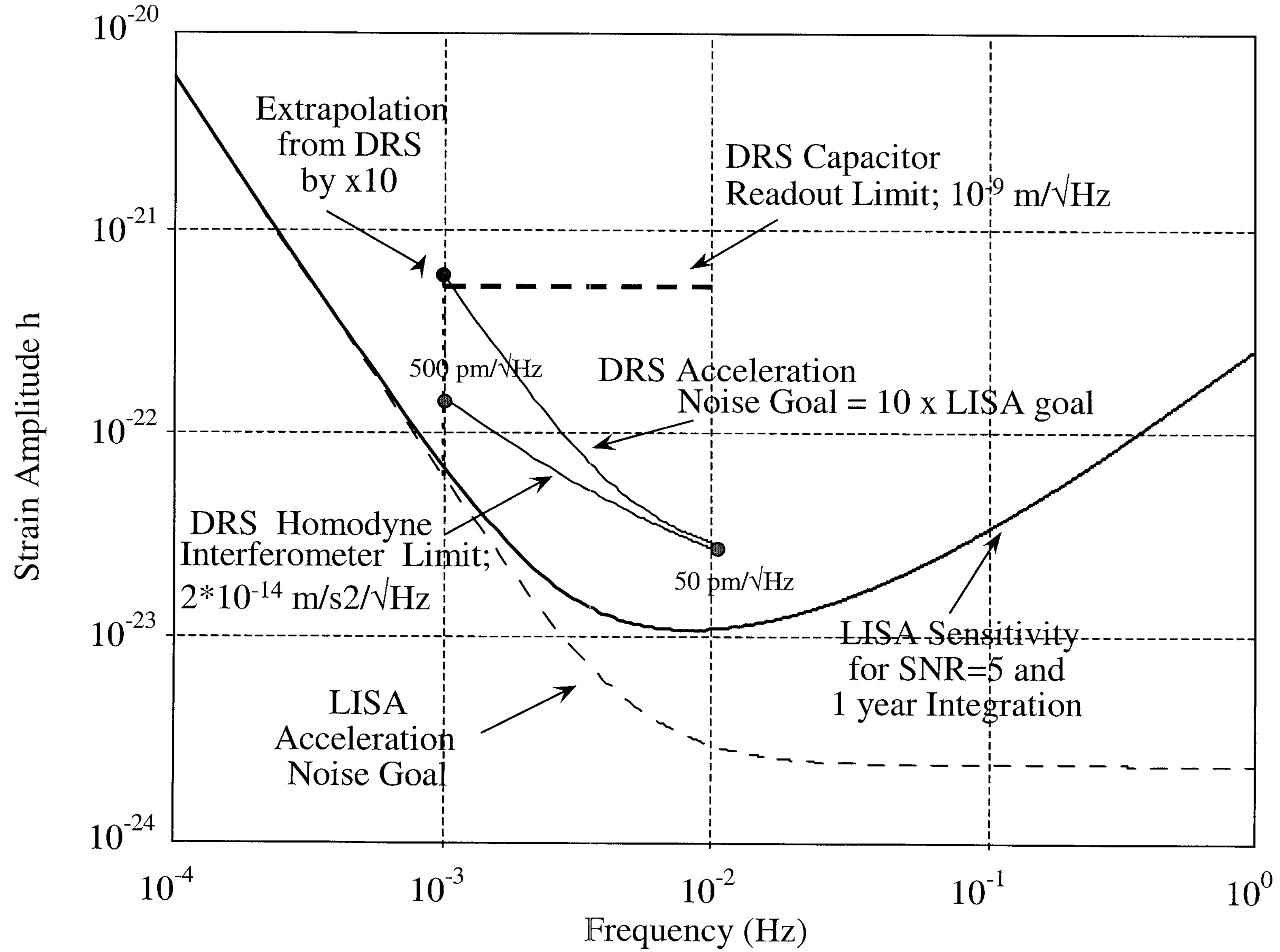
- LISA requirement @ 1 mHz: $3*10^{-15}$ m/s^2/√Hz
- Proof mass sensor noise: 1 nm/√Hz
- Interferometer noise @ 1 mHz; 500 pm/√Hz
- DRS goal @ 1 mHz: $3*10^{-14}$ m/s^2/√Hz

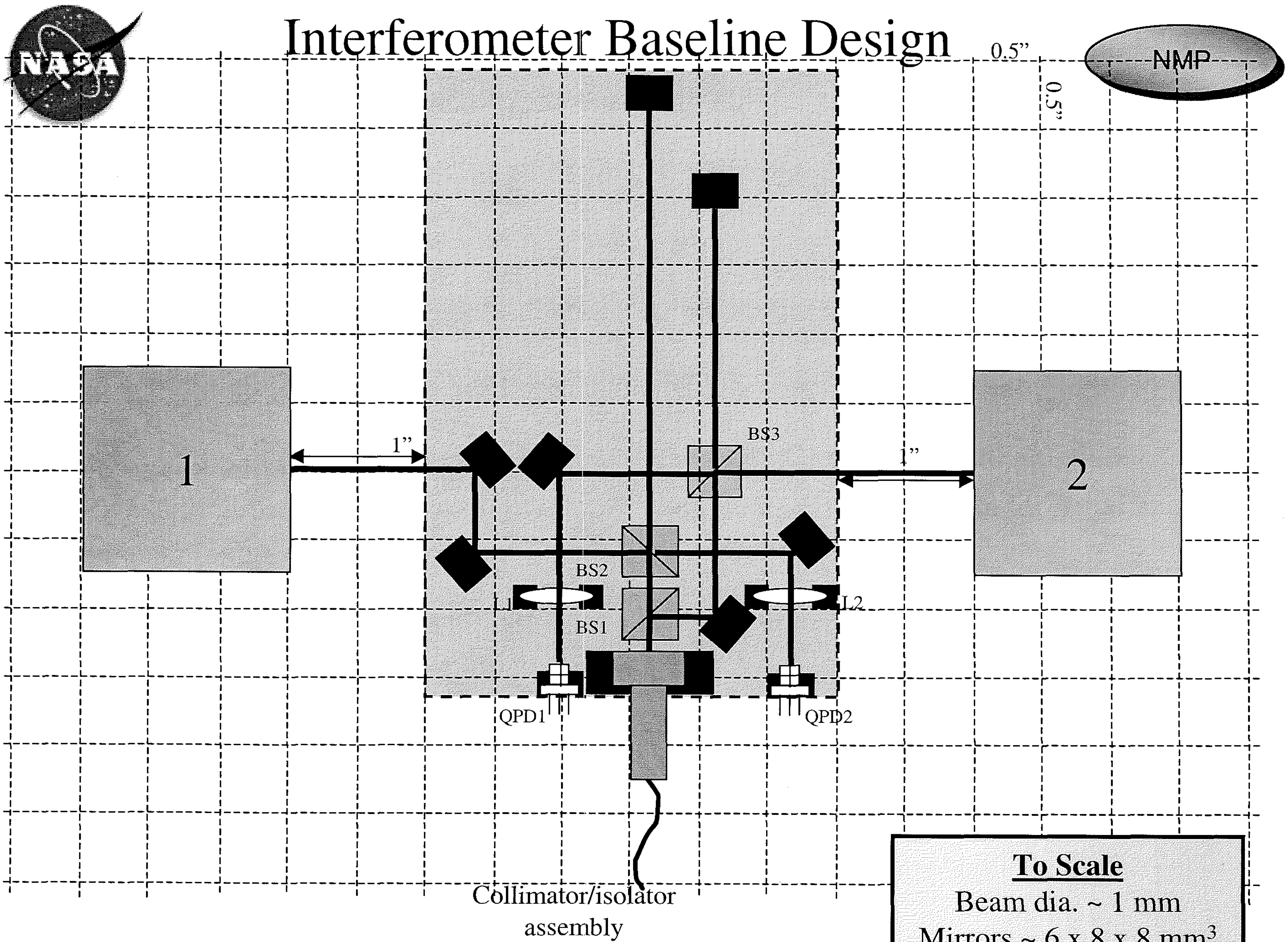
- LISA requirement @ 10 mHz: $1.5*10^{-14}$ m/s^2/√Hz
- Interferometer noise @ 10 mHz: 50 pm/√Hz
- DRS goal @ 10 mHz: $1.5*10^{-13}$ m/s^2/√Hz

- $a = (2\pi f)^2 * 5*10^{-10}$ m/√Hz ~ $2 * 10^{-14}$ m/s^2/√Hz @ 1 mHz
- $a = (2\pi f)^2 * 1*10^{-9}$ m/√Hz ~ $4 * 10^{-14}$ m/s^2/√Hz @ 1 mHz
- $4 * 10^{-12}$ m/s^2/√Hz @ 10 mHz)
- $a = (2\pi f)^2 * 5*10^{-11}$ m/√Hz ~ $2 * 10^{-13}$ m/s^2/√Hz @ 10 mHz

DRS Performance Limits



Interferometer Baseline Design



To Scale
Beam dia. ~ 1 mm
Mirrors ~ 6 x 8 x 8 mm^3
BS cubes ~ 8 x 8 x 8 mm^3

Laser Requirements

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- Average unstabilized laser noise seen: ~5.5 MHz/√Hz @ 10 mHz
- ~30 MHz/√Hz @ 1 mHz
- Interferometer pathlength mismatch: $\Delta L < 1$ mm

- Laser noise -> path noise: $\Delta x = \Delta L * \Delta\nu/\nu$
  - @ 10 mHz: < 20 pm/√Hz (avg.)
  - @ 1 mHz: < 100 pm/√Hz (avg.)

Compare to:

- Interferometer noise req'd: 50 pm/√Hz @ 10 mHz
- Interferometer noise req'd: 500 pm/√Hz @ 1 mHz

Proof Mass Stability

- Proof mass pointing stability: 1 μrad/$\sqrt{\text{Hz}}$ @ 1 mHz
  - associated displacement error: TBD

OPD error vs. Fringe Visibility/wavefront tilt

- OPD error due to changing fringe contrast @ max. slope of fringe signal (e.g due to proof mass tip/tilt):

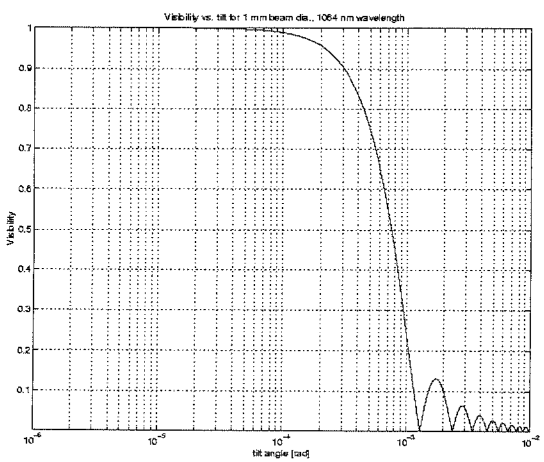
  Fringe signal: $I = I_0 * (1+V*\sin(4\pi*x/\lambda)\quad)$

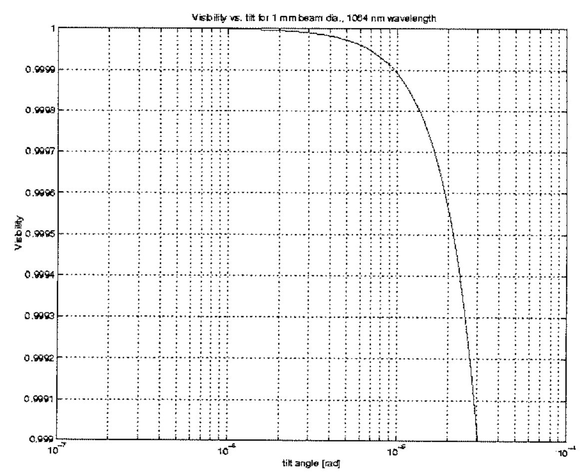
  $dI/I_0 = 4\pi V/\lambda*\cos(4\pi*x/\lambda)dx+\sin(4\pi*x/\lambda)dV$

  => @ $x=n*\lambda/4$ w/ n = 1,2,3,..(the max. slope of the fringe) $\sin(4\pi*x/\lambda)=0$,

  i.e. no sensitivity to visibility change dV. Q: How close can we get to that?

- With $V^2 = [2*J_1(\pi*\theta*D/\lambda)/(\pi*\theta*D/\lambda)]^2$ w/ θ angle between wave fronts, D - 1 mm, λ = 1064 nm we get a dV~10^{-5} (10 ppm) with the 1 μrad/$\sqrt{}$Hz @ 1 mHz proof mass pointing stability.





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OPD error vs. Signal (laser) Intensity

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- OPD error due to changing laser intensity I_0 :

$$dI/dI_0 = 1 + \sin(4\pi * x/\lambda) \text{ w/ } \quad \sin(4\pi * x/\lambda) = 0$$

$$@ \ x = n*\lambda/4$$

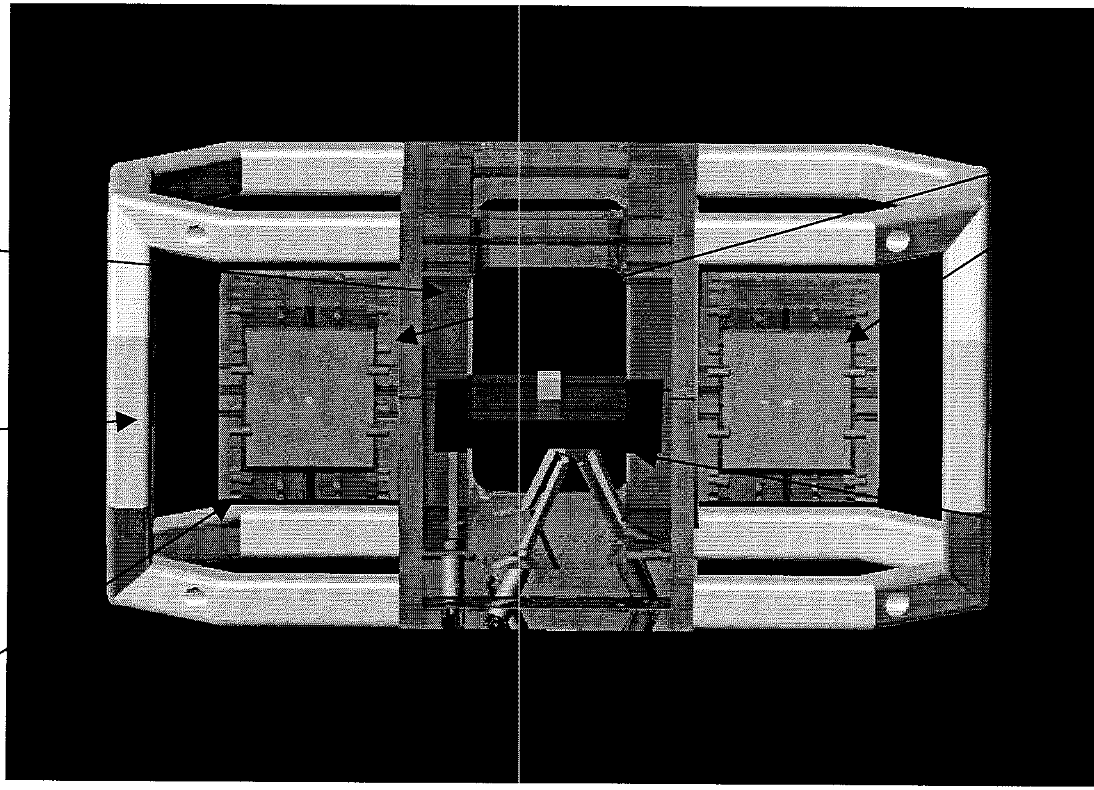
$$dI = dI_0$$

$$\text{using } dI/I_0 = 4\pi V/\lambda * \cos(4\pi * x/\lambda) * dx$$

we get an error of $dx = V*20$ pm for a signal (laser) intensity change $dI_0 \sim 2*10^{-4}$ @ $x \sim n*\lambda/4$.

Instrument Configuration

- Two gravitational reference sensors.
- Individual vacuum housings (not shown).
- Sensors integrated with interferometer.



Microthruster Concept

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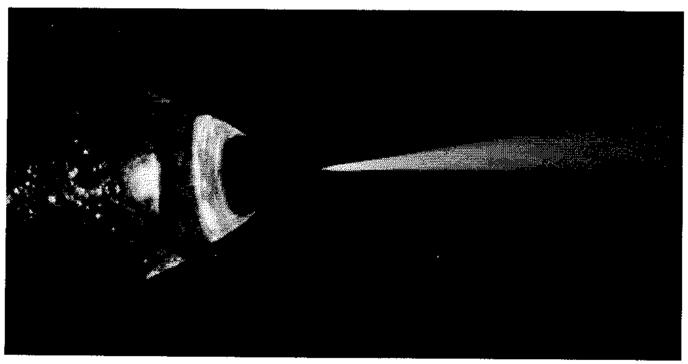
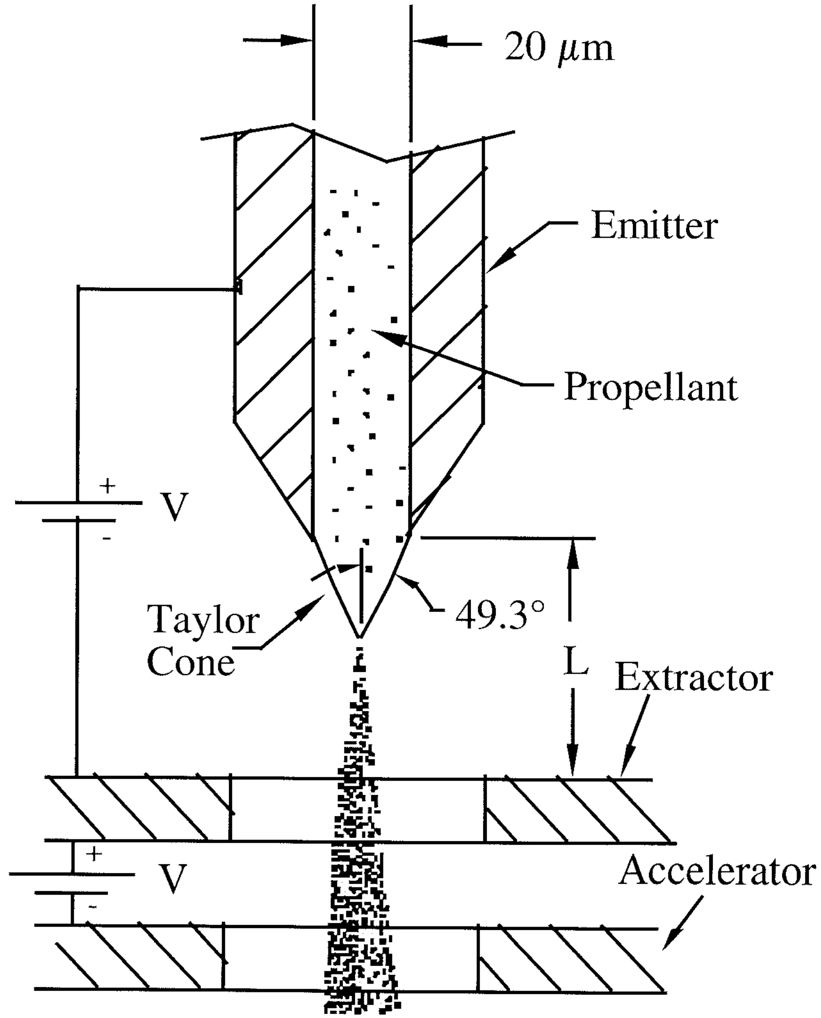
- Colloidal thrusters
  - Fluid fed through fine needle
  - High voltage extracts charged droplets
  - Droplets accelerated by high voltage
  - Thrust control of 0.1 μN through change of voltage or flow rate
  - Many needles can be combined to develop necessary thrust
  - Proportional thrust control allows precision position control
    - (displacement to thrust feedback loop)





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Microthruster Requirements

#	Item	Specification	Comment
1	Thrust	1– 20μN	Smoothly variable between end point values within 0.1μN
2	Thrust controllability/resolution	0.1μN	Must be within ±0.1μN from set point
3	Thrust noise	0.1 μN/$\sqrt{}$Hz from 10^{-3} Hz to 10^{-2} Hz	Stable over given period
4	Specific impulse	~ 500 sec	May vary depending on thrust
5	Thrust slew rate	< 0.5 μN/sec	Over voltage range/slower with flow
6	System mass	≤ 2 kg	Includes all thruster subsystem
7	Total system power	< 6.2 W	Average/thruster zeolite heater major consumer
8	Total operating time	≥ 2000 hours	90 days mission
Propulsion System Package			
– 8 thrusters in 4 clusters – Continuous/differential operation, authority over 6 DOF			

Microthruster Ground Test

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- Performance can be characterized in ground tests
  - Thrust levels inferred from beam current (time of flight spectrometry)
  - Torsional thrust stand verifies thrust to sub-μN levels (also at JPL)
  - Lifetime tests (emitter/electrochemistry and extractor/sputtering)
  - Mission profile simulation tests, life and dynamic response demonstration (thrust commands from simulated spacecraft computer)
  - Beam neutralization and beam profile measurements
    - Input to models to predict behavior in space
  - Contamination tests
    - Limited by back-scatter from test chambers (JPL)

Microthruster Flight/Validation Experiments

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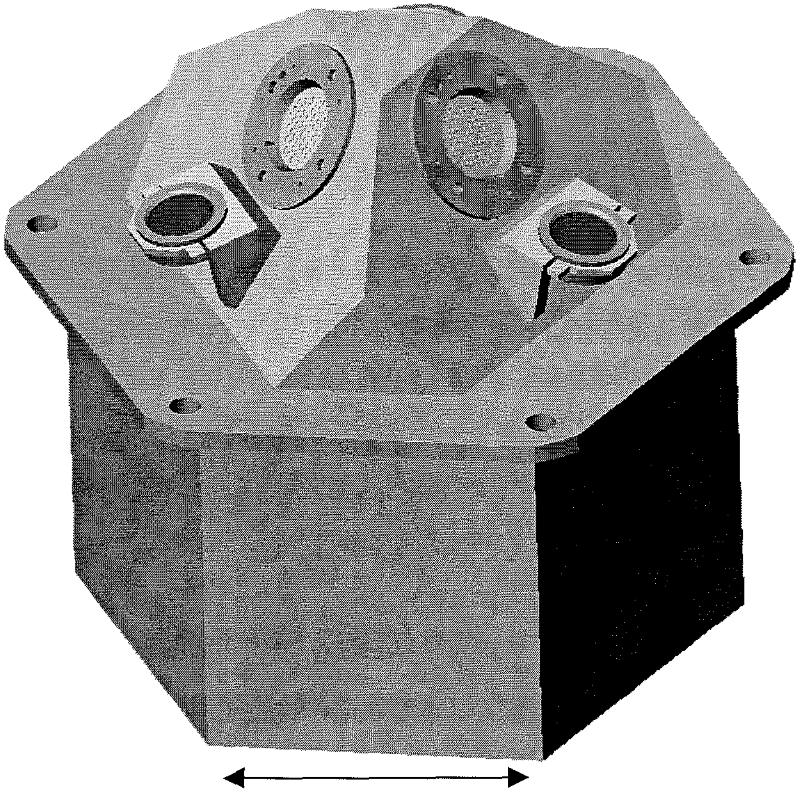

3 Thrusters Cluster concept

2 Thrusters Cluster baselined

- **Upon final orbit acquisition place GRS's in accelerometer mode**
- **Fire one thruster at a time**
- **Sweep 1 to 20 μN, compute calibration factors**
- **Hold steady $t \geq 1000$ sec. and record thrust noise at 3 levels of thrust**
- **Validate ground tests (thrust, noise, beam/neutralization)**
- **Repeat at middle and end of DRS operations**